

KIC8462852 Faded at an Average Rate of 0.165 ± 0.013 Magnitudes Per Century From 1890 To 1989

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ABSTRACT

The star KIC8462852 is a completely-ordinary F3 main sequence star, except that the light curve from the *Kepler* spacecraft shows episodes of unique and inexplicable day-long dips with up to 20% dimming. Here, I provide a light curve of 1232 Johnson B-band magnitudes from 1890 to 1989 taken from archival photographic plates at Harvard. KIC8462852 displays a highly significant and highly confident secular dimming at an average rate of 0.165 ± 0.013 magnitudes per century. From the early 1890s to the late 1980s, KIC8462852 has faded by 0.193 ± 0.030 mag. This century-long dimming is completely unprecedented for any F-type main sequence star. So the Harvard light curve provides the first confirmation (past the several dips seen in the *Kepler* light curve alone) that KIC8462852 has anything unusual going on. The century-long dimming and the day-long dips are both just extreme ends of a spectrum of timescales for unique dimming events, so by Ockham's Razor, all this is produced by one physical mechanism. This one mechanism does not appear as any isolated catastrophic event in the last century, but rather must be some ongoing process with continuous effects. Within the context of dust-occultation models, the century-long dimming trend requires 10^4 to 10^7 times as much dust as for the one deepest *Kepler* dip. Within the context of the comet-family idea, the century-long dimming trend requires an estimated 648,000 giant comets (each with 200 km diameter) all orchestrated to pass in front of the star within the last century.

Subject headings: stars: individual (KIC8462852) — stars: variables: general

1. Background

The star KIC8462852 (TYC 3162-665-1) is apparently a perfectly normal star, with no spectral peculiarities, appearing in the original Cygnus/Lyra field studied with the *Kepler* spacecraft. But then, the *Planet Hunters* project discovered in the *Kepler* light curve that KIC8462852 displays a unique series of aperiodic dips in brightness (Boyajian et al. 2015).

Boyajian et al. (2015) report a complete study of the properties of the star. KIC8462852 is a $V=11.705$ star ($B-V=0.557$) at 454 parsec distance. The surface temperature is 6750 K for spectral type of F3 V with no emission lines or anything unusual. Critically, the star does not have any infrared excess, with this being confirmed by Lisse et al. (2015), Marengo et al. (2015), and Thompson et al. (2015). With the exception of the *DASCH* light curve (see below), all data for KIC8462852 are from after the launch of *Kepler* in 2009. The *Kepler* light curve displays a series of dips, where the star faded by 0.2%–20% with durations from a day to weeks. Critically, Boyajian et al. (2015) make a very strong case that these unique dips cannot be caused by any data or analysis artifact.

The F3 star appears so normal, and such fast variations of such a main sequence star are inexplicable, so attention has been concentrated on the primary star being dimmed by occultation of circumstellar dust clumps. Boyajian et al. (2015) consider scenarios where the dust originated in a catastrophic collision in an asteroid belt, a giant impact between planets, and a family of comets. Most of the proposed scenarios are ruled out due to the lack of any infrared excess. Bodman & Quillen (2015) investigate the idea of a comet family, but find that they need implausibly-large comets in large numbers, plus a contrived disruption history. Further, the comet hypothesis cannot explain many of the dip light curves.

2. Photometry With The Harvard Archival Plates

The collection of $\approx 500,000$ sky photographs in the archives at Harvard College Observatory cover the entire sky from 1890 to 1989. However, few plates cover the sky from 1953 to 1969 due to the ‘Menzel Gap’. A typical glass plate has dimensions of 8×10 inch, stored in a paper envelope on shelves, with angular sizes from 11° – 42° wide. The limiting magnitude varies substantially from plate to plate, with a typical range from $B=14$ to fainter than $B=18$. Any given position is covered by 1000–4000 plates.

The Harvard plates are the original basis for what later became the Johnson B magnitude system. Despite the changes in emulsions over the years, the color sensitivity of the blue plates has been repeatedly measured to have a negligibly-small color term to the Johnson B system. For both sets of measures in this paper, the comparison sequence was taken from the AAVSO Photometric All-Sky Survey (*APASS*, see Henden & Munari 2014). The *APASS* magnitudes are accurately tied to the Johnson B system (Munari et al. 2014) through the standard stars of Landolt (2009).

Magnitudes for stars on the photographic plates are always taken by comparing some measure of the image diameter with the diameters of comparison stars on the same plate.

Historically, the dominant method was simply for an experienced human to visually examine the star images simultaneously under magnification. Image diameters were also mechanically measured with iris diaphragm photometers, and later with scanning techniques. From roughly the 1890s until the 1960s, these methods were one of the dominant tools for astronomers worldwide. Starting in the 1970s, photoelectric photometers and CCDs came to dominate, and the measuring of magnitudes from glass plates rapidly became a lost art. Today, only a few iris diaphragm photometers exist (almost all in museums). Currently, for visual estimates, only a few people in the world have any such knowledge, skill, or practice. The only alternative to by-eye estimates is to scan the plates and perform photometry from the scans.

2.1. *DASCH*

Many wonderful treasures are saved in the Harvard plates, but the reality is that the current generation of astronomers are mostly unaware of their existence. J. Grindlay has started and lead the work to completely digitize all $\approx 500,000$ plates (Grindlay et al. 2012; Tang et al. 2013). His program is called *Digital Access to a Sky Century @ Harvard (DASCH)*¹. The products are top-quality digitization for each plate (plus the envelope, plate markings, and logbook entry), plus fully-calibrated magnitudes for each stellar image on the plate. Currently, *DASCH* has completed only $\approx 15\%$ of the Harvard archives, and this includes all the plates covering the original Cygnus/Lyra *Kepler* field.

Boyajian et al. (2015) extracted the *DASCH* light curve for KIC8462852, as part of their collection of data from a wide variety of sources. They discussed this light curve in four sentences, concluding that “the star did not do anything spectacular over the past 100 years”. They also concluded that dips as seen with *Kepler* would have a high chance of not being visible in the historical Harvard light curve.

The *DASCH* analysis pipeline produces either magnitudes or limits for all 1581 plates covering the area of KIC8462852. For ordinary data quality selection, I reject plates with (1) ‘yellow’ or ‘red’ sensitive emulsion, (2) quality flags indicator, ‘AFLAGS’, >9000 , (3) one-sigma error bars >0.33 mag, or (4) the target within 0.2 magnitudes of the quoted plate limit. With these selections, I have 1232 magnitudes from *DASCH*. Critically, the removal or extension of any or all of these cuts does not significantly change the slope of the light curves for KIC8462852, its check stars, or any constant star.

¹<http://dasch.rc.fas.harvard.edu/index.php>

2.2. Visual Estimates

Visual estimates are made with the plate placed on a light table, and the star field is examined with magnification provided by a low-power microscope, or more commonly with a loupe placed onto the glass side of the plate. The image diameter of the target is judged in comparison to the image diameters of each of the comparison stars in turn, and the brightness of the target is evaluated as being some fraction between two comparison stars. For a characteristic example, a target judged as halfway between comparison stars with magnitudes 12.3 and 12.7 mag would be taken to be 12.5 mag in brightness. The human eye is remarkably good at such side-by-side comparison of the diameter of small circles. Inexperienced workers have an accuracy of ~ 0.3 mag, while experienced observers get to ~ 0.1 mag accuracy for typical plates and sequences. I have had very extensive practice at measuring magnitudes at Harvard and plate archives worldwide, continuously from 1979 to the present (e.g., Schaefer 1990; 2014a; 2014b; Schaefer et al. 2008; Schaefer & Patterson 1983) plus substantial work on the theory of photographic magnitudes (e.g., Schaefer 1979; 1981; 1983; 1995).

For the by-eye light curve of KIC8462852, I visited Harvard in October 2015. I selected plates for a wide distribution in time from the patrol series (DNB, RH, and AC) as well as deep series (A, MC, and I). For the plates pulled from the shelves and put on a light table, with examination under a $10\times$ loupe, I continued only for those plates which I judged to be able to return a confident and accurate magnitude. With this, I measured 131 magnitudes of KIC8462852 from 1890–1989.

2.3. Comparison of Methods

Visual measures have the advantages of being fast, cheap, and simple, whereas scanning methods are always slow, expensive, and complex. The *DASCH* photometry has the advantages that all useable plates were measured, that realistic error bars are calculated for each plate individually, that the photometry is purely objective with no ‘personal equation’, and that nearby check stars can be handled in a manner identical to the target star.

Under ordinary situations, an experienced eye has a photometric accuracy that is $1\times$ to $3\times$ more accurate than *DASCH* (e.g., Schaefer 2014a; 2014b). This result is from several ‘blind’ methods for many stars, for example by measuring the RMS scatter throughout the folded light curve of a variable star with a roughly-sinusoidal light curve. For the case of KIC8462852, I find that the real uncertainty in the magnitudes are close to being equal for the *DASCH* and the by-eye measures.

3. KIC8462852 From 1890 to 1989

With these procedures, I have created two independent Johnson B light curves for KIC8462852 from 1890 to 1989 from the same set of Harvard plates, the first with 1232 plates with *DASCH* magnitudes, and the second with 131 plates with my by-eye measures. With this, a simple plot of the light curve shows scatter such that it is difficult to pick out dips, eruptions, secular trends, or any variability with amplitude smaller than a quarter of a magnitude or so. Hence, I have grouped the magnitudes into five year bins. For the magnitudes in each bin, I have calculated the RMS scatter and I take the one-sigma error bar on the bin average to be the RMS divided by the square root of the number of plates in that bin. Table 1 and Figure 1 present this KIC8462852 light curve from *DASCH*.

With three methods, I find that the average error bar for individual plates is close to 0.13 mag: (1) For the *DASCH* light curve, in the 5-year time bins, the average RMS scatter of the individual magnitudes is 0.12 mag. If KIC8462852 is variable in these half-decade intervals, then the average error bar for measuring one plate is <0.12 mag. (2) *DASCH* calculates realistic error bars for individual plates. For KIC8462852, the median is 0.15 mag, with a central 68% range of 0.10-0.21 mag. (3) The differences between by-eye and *DASCH* magnitudes of the same plate have an RMS of 0.19 mag, so the average one-sigma uncertainty in one measure of the plate is $0.19/\sqrt{2}=0.13$ mag.

An excellent method to measure the real systematic errors in the *DASCH* light curve is to derive the light curves of check stars with identical procedures. I have used the same procedures and selections to produce *DASCH* light curves for five nearby stars with similar magnitudes as KIC8462852. All five give similar results, so I will report here in detail on only the two check stars closest in color and brightness to KIC8462852. The first check star is TYC 3162-1001-1 with $B - V=0.57$, while the second check star is TYC 3162-879-1 with $B - V=0.77$ (Hog et al. 2000). I have averaged the check star magnitudes into five-year bins (Table 1, Figure 1). The five-year binned data have an RMS scatter in these two light curves is 0.024 and 0.034 mag. The best fit linear trend (from a chi-square fit) gives slopes of -0.028 ± 0.011 and $+0.027\pm 0.014$ magnitudes per century. These results show that check stars have constant light curves to a level of 0.03 mag over a full hundred years.

The light curve displays highly significant variations, with a clear trend for fading from early to late times. A chi-square fit with a flat light curve yields $\chi^2=197.7$, while a sloped line yields $\chi^2=37.8$. A chi-square fit for a linear trend has a slope of $+0.165\pm 0.013$ magnitudes per century. The check star light curves do not have any significant slope, and this proves that systematic errors are not creating the slope for KIC8462852.

My by-eye light curve also has an obvious slope. A chi-square fit to all 131 magnitudes

from 1890 to 1989 yields a slope of $+0.310 \pm 0.029$ magnitudes per century. This is formally different from the slope that I get from *DASCH*, and I attribute this to the happenstance that my sampling of the available plates included few from 1900-1909, when the light curve was relatively dim and pulling the fitted slope to smaller values. The critical point from my by-eye measures is that KIC8462852 does indeed have a highly significant variation, manifesting as a secular fading from the 1890s to the 1980s. This proves that the secular trend is not due to any issues with the *DASCH* procedures, measures, analysis, or selection.

The long-term trend in the *DASCH* light curve can be described in various ways. One way is simply to note that KIC8462852 faded from $B=12.265 \pm 0.028$ in 1892.5 to $B=12.458 \pm 0.012$ in 1987.5, for a total fading of 0.193 ± 0.030 mag in 95 years. This fade rate is $+0.203 \pm 0.032$ magnitudes per century (dashed line in Figure 1). This end-to-end trend line provides an excellent representation of all the Harvard data *except* for the decade from 1900-1909. The individual plates for this decade show a similar distribution of magnitudes as in adjacent decades, except that there are many more fainter magnitudes (from 12.6-13.0). This might be due to the star suffering many deep dips during the years 1900-1909. The light curve has an alternative description that it has a secular trend that is not steady. That is, the average decline rate is $+0.165 \pm 0.013$ magnitudes per century, but there are stutters built on top of this (thick line in Figure 1).

4. Implications

The KIC8462852 light curve from 1890 to 1989 shows a highly significant secular trend in fading over 100 years, with this being completely unprecedented for any F-type main sequence star. Such stars should be very stable in brightness, with evolution making for changes only on time scales of many millions of years. So the Harvard data alone prove that KIC8462852 has unique and large-amplitude photometric variations. Previously, the *only* evidence that KIC8462852 was unusual in any way was a few dips in magnitude as observed by one satellite, so inevitably we have to wonder whether the whole story is just some problem with *Kepler*. Boyajian et al. (2015) had already made a convincing case that the dips were not caused by any data or analysis artifacts, and their case is strong. Nevertheless, it is comforting to know from two independent sources that KIC8462852 is displaying unique and inexplicable photometric variations.

KIC8462852 is suffering a century-long secular fading, and this is contrary to the the various speculation that the obscuring dust was created by some singular catastrophic event. If any such singular event happened after around 1920, then the prior light curve should appear perfectly flat, whereas there is significant variability before 1920. If the trend is

caused by multiple small catastrophic events, then it is difficult to understand how they can time themselves so as to mimic the trend from 1890-1989. In the context of the idea that the star is undergoing a Late Heavy Bombardment (Lisse et al. 2015), it is implausible that such a mechanism could start up on a time scale of a century, or that it would start so smoothly with many well-spaced collisions.

KIC8462852 displays *two* types of unique dimming episodes (the dips from *Kepler* and the fading from Harvard) and these must be causally related and coming from the same mechanism. That is, Ockham’s Razor tells us that it is very unlikely that one star will suffer two different mechanisms that are unique to that star and that both are only manifest in dimming the starlight by up to 20%. The timescales differ greatly, from a day for the *Kepler* dips up to a century for the Harvard light curve fading. However, dimming events with intermediate timescales are also seen (e.g., the 1900-1909 decade and the last hundred days of the *Kepler* light curve), so apparently there is a continuum of timescales available for the one dimming mechanism. So if the day-long dips are caused by circumstellar dust occultations, then the century-long fading must also be caused by circumstellar dust occultations.

Within the various dust-occultation ideas, there is some quantity of dust ($M_{dust,1dip}$) required to create the one deepest dip (20% extinction with a duration of around one day), which only dims the star from the *Kepler* baseline level. Boyajian et al. (2015) and Thompson et al. (2015) calculate a lower limit on $M_{dust,1dip}$ of $10^{-9} M_{\oplus}$. Bodman & Quillen (2015) calculate that the comet family scenario requires 36 giant-comets with 200 km diameters to produce enough dust.

The no-circumstellar-extinction level of the star is $>0.193 \pm 0.030$ mag brighter in the 1890s than is the *Kepler* baseline, so any dust-occultation idea also requires that the star be covered by a second portion of dust, roughly $M_{dust,1dip}$, just to dim the star by around 20% down to the *Kepler* baseline. The time for this given mass of dust to cross over the star is of order one day (as based on the dip duration), so in the day after the deepest *Kepler* dip there must be some fresh supply of dust that keeps the star dimmed to the *Kepler* baseline. Over the whole 1500 days of the *Kepler* light curve, the total dust needed will be $1503 M_{dust,1dip}$ with $1500 M_{dust,1dip}$ simply to dim the star down to the *Kepler* baseline plus $3 M_{dust,1dip}$ to produce all the *Kepler* dips. The dust extinction from 1890 observed in the Harvard plates is not constant, and gets to near 20% below the brightest level only towards the end of the century. With a linear decline, the required dust production would be equivalent to the full 20% for half a century. This will provide a lower limit, since it has ignored the extra dimming from 1900-1909, while the real no-circumstellar-extinction level of the star could well be brighter than seen in the 1890s. Half a century is roughly 18,000 days, so the fading as seen with the Harvard plates requires $>18,000 M_{dust,1dip}$. And that is just for the dust that

has happened to pass in front of the star. If the star’s dust inventory is not confined to orbits that have it all passing in front of the star in the last century, then some roughly spherical distribution can be expected. For dust at a distance of R from the star, the total dust mass would then be $(R/R_*)^2 \times M_{dust,1dip}$ just to dim the star down to the *Kepler* baseline. The radius of the star (R_*) is $1.58 R_\odot$ and the dust is from 3–30 AU from the star (Boyajian et al. 2015), so some roughly isotropic dust distribution will require 170,000 to 17,000,000 times $M_{dust,1dip}$. In all, the dimming shown in the Harvard light curve requires that there be of order 10^4 to 10^7 times as much dust as has been previously modeled from the *Kepler* dips alone.

With $M_{dust,1dip} \gtrsim 10^{-9} M_\oplus$, the dimming of the Harvard light curve requires of order 10^{-5} to $10^{-2} M_\oplus$ of dust around KIC8462852. Thompson et al. (2015) have used SCUBA-2 sub-millimeter observations to place limits on the total dust mass around the star, with a limit of $\leq 3.0 \times 10^{-6} M_\oplus$ for dust 2–8 AU from the star and a limit of $\leq 5.6 \times 10^{-3} M_\oplus$ for dust out to 26 AU from the star. The only way to reconcile these limits with the fading in the Harvard light curve, is to require that the dust be confined to a volume around a plane (like for an orbit or a disk) and/or to be far from the star.

With 36 giant-comets required to make the one 20% *Kepler* dip, and all of these along one orbit, we would need 648,000 giant-comets to create the century-long fading. For these 200 km diameter giant-comets having a density of 1 gm cm^{-3} , each will have a mass of $4 \times 10^{21} \text{ gm}$, and the total will have a mass of $0.4 M_\oplus$. This can be compared to the largest known comet in our own Solar System (Comet Hale-Bopp) with a diameter of 60 km. This can also be compared to the entire mass of the Kuiper Belt at around $0.1 M_\oplus$ (Gladman et al. 2001). I do not see how it is possible for something like 648,000 giant-comets to exist around one star, nor to have their orbits orchestrated so as to all pass in front of the star within the last century. So I take this century-long dimming as a strong argument against the comet-family hypothesis to explain the *Kepler* dips.

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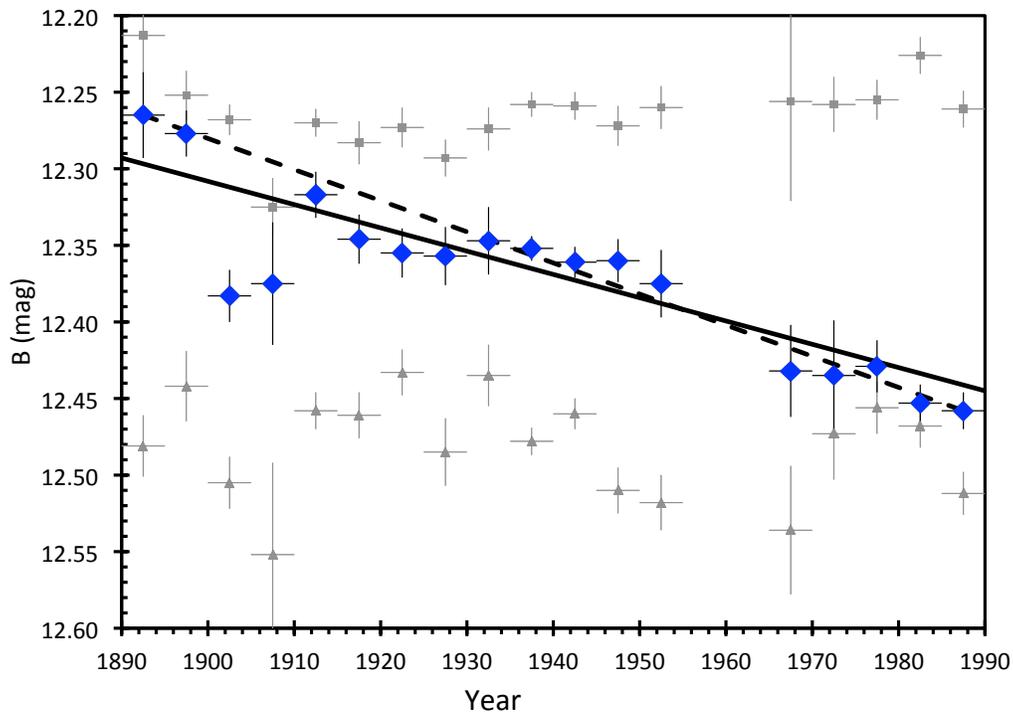


Fig. 1.— The 5-year binned *DASCH* light curve of KIC8462852 (large blue diamonds). The star shows highly significant fading from 1890 to 1989. The light curves for the two check stars with colors close to that of KIC8462852 are displayed in the figure with grey squares (TYC 3162-1001-1) and triangles (TYC 3162-879-1). The dashed line is a simple linear trend connecting the two end points, while the solid line is the chi-square fit result. The secular trend for KIC8462852 can be viewed either as a steady fading of 0.203 ± 0.032 mag/century with substantial dips from 1900-1909, or as an unsteady decline averaging 0.165 ± 0.013 mag/century.

Table 1. Harvard light curve of KIC8462852 and two check stars

Year	Plates	RMS (mag)	KIC8462852 B (mag)	TYC 3162-1001-1 B (mag)	TYC 3162-879-1 B (mag)
1892.5 ± 2.5	13	0.101	12.265 ± 0.028	11.713 ± 0.025	12.451 ± 0.020
1897.5 ± 2.5	41	0.097	12.277 ± 0.015	11.752 ± 0.016	12.412 ± 0.023
1902.5 ± 2.5	96	0.165	12.383 ± 0.017	11.768 ± 0.010	12.475 ± 0.017
1907.5 ± 2.5	17	0.166	12.375 ± 0.040	11.825 ± 0.019	12.522 ± 0.060
1912.5 ± 2.5	92	0.140	12.317 ± 0.015	11.770 ± 0.009	12.428 ± 0.012
1917.5 ± 2.5	66	0.128	12.346 ± 0.016	11.783 ± 0.014	12.431 ± 0.015
1922.5 ± 2.5	33	0.093	12.355 ± 0.016	11.773 ± 0.013	12.403 ± 0.015
1927.5 ± 2.5	72	0.161	12.357 ± 0.019	11.793 ± 0.012	12.455 ± 0.022
1932.5 ± 2.5	64	0.176	12.347 ± 0.022	11.774 ± 0.014	12.405 ± 0.020
1937.5 ± 2.5	205	0.116	12.352 ± 0.008	11.758 ± 0.008	12.448 ± 0.009
1942.5 ± 2.5	141	0.125	12.361 ± 0.010	11.759 ± 0.009	12.430 ± 0.010
1947.5 ± 2.5	80	0.124	12.360 ± 0.014	11.772 ± 0.013	12.480 ± 0.015
1952.5 ± 2.5	62	0.170	12.375 ± 0.022	11.760 ± 0.014	12.488 ± 0.018
1967.5 ± 2.5	6	0.073	12.432 ± 0.030	11.756 ± 0.065	12.506 ± 0.042
1972.5 ± 2.5	10	0.114	12.435 ± 0.036	11.758 ± 0.018	12.443 ± 0.030
1977.5 ± 2.5	56	0.130	12.429 ± 0.017	11.755 ± 0.013	12.426 ± 0.017
1982.5 ± 2.5	86	0.107	12.453 ± 0.012	11.726 ± 0.012	12.438 ± 0.014
1987.5 ± 2.5	92	0.116	12.458 ± 0.012	11.761 ± 0.012	12.482 ± 0.014